NAVAL SUBMARINE MEDICAL RESEARCH LABORATORY

SUBMARINE BASE, GROTON, CONN.

REPORT NUMBER 930

A COMPARISON OF COMPUTERIZED AUDIOMETRY BY ANSI, BEKESY FIXED-FREQUENCY, and MODIFIED ISO PROCEDURES IN AN INDUSTRIAL HEARING CONSERVATION PROGRAM

by

J. Donald Harris

Naval Medical Research and Development Command
Research Work Unit MF58.524.023-2017

Released by:

R. A. Margulies, CAPT, MC, USN
Commanding Officer
Naval Submarine Medical Research Laboratory

July 1981

A COMPARISON OF COMPUTERIZED AUDIOMETRY BY ANSI, BEKESY FIXED-FREQUENCY, AND MODIFIED ISO PROCEDURES IN AN INDUSTRIAL HEARING CONSERVATION PROGRAM

J. DONALD HARRIS
Naval Submarine Medical Research Laboratory
Submarine Base, New London, Connecticut 06240

SUMMARY PAGE

THE PROBLEM:

To determine the most powerful and most cost-effective audiometric threshold program for incorporating into the Navy's forthcoming nationwide computerized audiometric data-collection and -management system.

FINDINGS:

An adaptive version of widely-used Bekesy-type self-recording audiometry was developed which takes advantage of the ability of the minicomputer to adjust its speed and other characteristics to interact with the behavior of the test person. This version (the NSMRL Mark I Computerized Bekesy System) when applied to 50 individuals in the Navy Hearing Conservation Program was found equal to or, more usually, superior to two other widely-recommended programs.

APPLICATION:

For the use of otologists, industrial health physicians, audiologists and others involved in making decisions on design and purchase of audiometric equipment.

ADMINISTRATIVE INFORMATION

This investigation was conducted as part of Naval Medical Research and Development Command Research Work Unit Number MF58.524.023–2017, "Concurrent Validation of Audiometer Computer Paradigms for Navy Hearing Conservation Programs." The present report was submitted for review in May 1980, approved for publication on 27 May, 1980 and designated NavSubMedRschLab Report No. 930.

ABSTRACT

Three audiometric procedures were programmed at .5, 1, 2, 3, 4, and 6 kHz and presented on test and retest to 50 persons: (1) a version of the Amer. Nat'l. Standards Inst. guidelines (the "10-dB down–up 5 dB" rule) incorporating time-window response validation, (2) a slight modification of the procedure recommended by the Internat'l. Standards Organization, and (3) the NSMRL Mark I Bekesy-type system (a) incorporating numerous quality controls, (b) providing not only an estimate of Hearing Threshold Level (HTL) to the nearest dB but providing also an estimate of the confidence to be placed in each HTL, and (c) continuously adapting its parameters to interact with the behavior of the testee. Initial threshold-seeking runs, if they yielded no HTL or if response pattern did not meet quality standards (about 10% of all initial runs) were immediately followed by a second exactly similar run. This step yielded acceptable HTLs in 96.2% of all cases, about the same for all procedures. Six Ss accounted for 2/3 of failures. Test-retest reliability was high (r = .83–.98) except that the ANSI procedure was less so at .5, 1, and 2 kHz (r = .72–.78). Test and retest group-mean HTLs never changed by as much as 2 dB. Individual test-retest differences of 5 dB or less were found in 90.7 % of cases for the Mark I, compared with 65.5% reported by Cluff (1980) using a standard Grason-Stadler 1703 Bekesy audiometer. ISO HTLs were fainter by 3.6, 2.9, 3.7, 3.3, 2.7, and 5.7 dB than ANSI HTLs, while the Mark I HTLs were fainter than ANSI HTLs by 4.0, 4.0, 6.7, 5.6, 4.9, and 4.7 dB in the usual frequency order. Prediction of an individual S's HTLs by any procedure could be accomplished as efficiently from any other procedure as could prediction from test to retest within any procedure. Estimated time to complete a two-ear audiogram on the average S was 10.5 ± 1.07 min for the ANSI, 9.25 ± 0.63 min for the ISO, and 3.35 ± 0.35 min for the Mark I; average savings for individual Ss with the Mark I vs the ANSI procedure was 7.27 min (range 4.3–20.2 min). It was shown that HTLs furnished by a computerized adaptive Bekesy system can profitably be reported to the nearest 2.5 dB. The Mark I system was shown, by all criteria examined here, to be the equal of, or more usually superior to, the other classes of procedure as the audiometric method of choice in hearing conservation programs.

A COMPARISON OF COMPUTERIZED AUDIOMETRY BY ANSI, BEKESY FIXED-FREQUENCY, AND MODIFIED ISO PROCEDURES IN AN INDUSTRIAL HEARING CONSERVATION PROGRAM

J. DONALD HARRIS
Naval Submarine Medical Research Laboratory
Submarine Base, Groton, Connecticut 06240

INTRODUCTION

The large numbers of persons for whom reference and monitoring audiometry are needed in a hearing conservation program (HCP) usually exceeds by far the capacity of the currently available supply of nationally certified audiologists to administer. A number of compromises have therefore been adopted, including (a) group and screening audiometry, (b) the development of relatively automatic self-recording (Bekesy-type) audiometry by the psychophysical method of adjustments, (c) the quick training of audiometric technicians whose case load is presumably restricted to the generally uncomplicated problem of unmasked AC hearing threshold levels (HTLs) on a normal or near-normal population, and (d) the development of computer-assisted procedures to take some of the burden off the shoulders of audiometric technicians in administering the stimuli and in interpreting responses.

The development by Rudmose (McMurray and Rudmose, 1956) of a standardizable Bekesy fixed-frequency audiometer and the simultaneous development of a prototype of a unit designed to simulate closely audiometry by the traditional psychophysical method of limits (Brogan, 1956) have led today to a variety of commercial audiometers representing these and other systems used in HCPs here and abroad.

Most recently the advent of the minicomputer into audiometry (Weiss, 1961) has made possible advancements in reliability and validity and particularly in cost effectiveness in those audiometric systems where computerization has been applied. Specifically, computerization has made possible a hitherto unknown standardization of stimulus presentation in tone duration, intertone intervals, and pattern of intensity levels; it has made possible a validation of each response of a subject in ways not available to the unaided manual audiometrist; and it has made available an instant and entirely objective calculation of HTL without depending upon the audiometric technician's memory, notes, or clerical accuracy. Thus the judgments, and consequently the training, of the audiometric technician can be reduced to the barest minimum of initially instructing the subject and referring to an audiologist for individual attention those whom the computer labels "untestable."

There are now appearing papers comparing versions of computerized with traditional audiometry. A computerized version of the "–10 +5 dB" procedure (Hughson and Westlake, 1944) was favorably compared (Harris, 1978) with manual audiometry by qualified audiologists using ASHA guidelines (anon, ASHA, 1978). (In this work it was found that a slightly shorter version of the ASHA guidelines, the ANSI guidelines (anon, ANSI, 1977) was no less reliable and was somewhat more cost effective.)

It was shown (D.A.Harris, 1979a) in an industrial population of 50 aerospace workers that a commercial computerized unit simulating the ASHA guidelines compared favorably with a commercial non-computerized Bekesy unit, the latter, however, yielding mean HTLs fainter by from 2.3 – 6.7 dB. On the other hand, the Pearson correlations between each set of individual HTLs for separate frequencies were of the order of .90 or higher, so that it was clear that the two systems were mutually convertible the one to the other.

Mean HTLs from a computerized version of Bekesy fixed-frequency audiometry on 24 Ss compared favorably with mean HTLs from a typical commercial Bekesy unit (Grason-Stadler Model 1703A) (Harris and Smith, 1979). Correlations between the best estimates of HTLs for the two systems were of the order of .90 for frequencies 0.5–8 kHz. The NSMRL Mark I version adapted attenuation rates throughout the program to suit each S's speed of response, imposed three quality controls on the goodness of S's individual and total responses, and printed HTL as the mean of the midpoints of 4 (or, if necessary, 6) acceptable threshold-crossing series together with the average deviation (AD) of these midpoints from the final mean.

On 12 normal-hearing young adults (24 ears), mean HTLs from manual audiometry were compared as a standard with a commercial Bekesy unit (Tracor ARJ-4C) and with a computerized version based upon the ASHA guidelines (Tracor RA-410) (D.A.Harris, 1979b). Mean manual HTLs were from 0.2 – 4.4 dB fainter than those from the computerized version (except at 3 kHz where the RA-410 HTLs were fainter), and were from 1.0–9 dB louder than the Bekesy mean HTLs at all frequencies. (The divergence of the Bekesy from manual HTLs was confirmed by Cluff (1980) who found in 31 noise-exposed adults individual divergences of more than 5 dB in 36% of 217 HTLs; though there were indeed 15.6% of such divergences in test vs retest of careful standard manual audiometry). From the study of Cluff it should also be noted that there was no significant difference as a function of frequency between the manual vs the Bekesy individual HTLs; nor was there such a difference between Bekesy HTLs collected under "casual" instructions vs instructions "very thorough. . .and . . .monitored carefully" with interruptions and reinstruction.

Robertson et al (1979), Loyborg et al (1980 and Schientz (1980) have evaluated commercial instruments incorporating some versions of the ASHA guidelines.

The present study compared, with a typical industrial population data from 3 computerized audiometric programs, one built on the ANSI guidelines, one (the NSMRL Mark I) a version of Bekesy audiometry, and a slightly shortened version of the current ISO method (anon, ISO, 1977).

METHOD

Subjects

These were the first 50 persons available for a half hour special testing, both uniformed and civilian, aged 17–65 yrs, drawn from a much larger number enrolled in the Navy's HCP. Only one ear, in most cases the L, was used.

Equipment

A Hewlett-Packard frequency synthesizer was connected through usual amplification and programmable attenuation circuits to a Telephonics TDH-39 earphone in an MX cushion. S responded with the same handswitch in all programs. All timing and response analyses were accomplished with a PDP-11 computer with a terminal in the NSMRL Sound Suite. S sat in an anechoic chamber of about 1200 cu. ft. Calibration in SPL was performed with standard Bruel & Kjaer equipment and an NBS 9A coupler.

Audiometric Technicians

The writer tested an occasional S, but the bulk of the data were collected by Deborah Kopko and Kathy Levanti, to whom this paper owes much. These persons scheduled and seated the S, adjusted the earphone, and gave minimal verbal instructions. They then keyboarded a "Start" command to the computer, initiated a retake of a threshold-seeking run when the computer called for it, and initiated a "Print" command when the computer indicated the audiogram was completed, whether with all 6 HTLs satisfactorily established or not as the case may have been.

Procedure

Ss were assigned in a semi-random order to the 6 audiograms (3 procedures, test-retest each). Approximately equal numbers were given each of the 3 tests first. A test was not always followed next by its retest.

ANSI Test

A description is in Harris (1978). Each tone was 1 sec in duration, rise-fall of 10 msec, intertone interval of 2 ± 0.8 sec (i.e., about 15.8 tones/min). Response was validated by a time-window requirement:

(1) a switch on-response prior to 50 msec after initiation of a tone was ruled invalid and delayed the next tone by 2 sec;

(2)an on-response from 50 msec after tone initiation to tone termination was ruled valid;

(3) an off-response prior to 50 msec after termination of tone was ruled invalid; and

(4) an off-response from 50 msec to 250 msec after termination of tone was ruled valid.

Both on-response and off-response had to be ruled valid before that tone presentation was scored "accept."

The first tone was at 40 dB HL (ANSI 1969). If response was invalid ("NO")

the levels increased in 10-dB steps until a valid ("YES") response appeared, whereupon a descending series in 10-dB steps was run until an invalid or no response occurred. The "−10 +5 dB" rule was thereupon followed until on 2 ascending series out of 4 (or fewer) a certain HL yielded congruent valid responses.

In case the first tone at 40 dB HL yielded a valid response, the first series was of course descending.

In case after 4 ascending series no single level yielded criterion, the whole run was replicated at once, and accepted if the "2-congruent" criterion was then reached. In case neither run yielded criterion, S was labeled "untestable" at that frequency and the computer went to the next frequency.

NSMRL Mark I (Bekesy) Test (See Fig. 1)

A description is in Harris and Smith (1979). A train of pulses (250 msec on, 150 msec off; i.e., 2.5/sec) started at 40 dB HL and ascended at 10 dB/sec until S pressed the switch, then descended at 10 dB/sec until S released the switch. At that point ascending-descending series began at 5 dB/sec. If quality controls were met, the program stopped after 4 threshold crossings at 5 dB/sec, and printed out the mean of the 4 midpoints, and their AD, to the nearest 0.1 dB.

Quality controls included:

(1) stopping a threshold-seeking run and starting a second at 40 dB HL whenever the end of a descending series was at a HL 5 dB louder than the end of any ascending series; or the end of an ascending series was at a HL fainter by 5 dB than the end of any previous descending series (these events would signal an unacceptable threshold "drift" in either direction as the run progressed).

(2) When a series at 5 dB/sec, either descending or ascending, equaled or exceeded 10 dB, the attenuation rate slowed to 2.5 dB/sec; and if at that rate a series equalled or exceeded 15 dB, the run stopped and a second one started immediately at 40 dB HL. If a second run did not yield an acceptable HTL, the computer labeled S "untestable" and went to the next frequency.

(3) When after 4 threshold-crossing series the AD of the 4 midpoint values exceeded 2.0 dB, 2 more series were run and the mean and AD printed excluding the 2 most divergent series.

Modified ISO Test (Anon, ISO, 1977)

S responded to each 250-msec tone. Intertone interval was 2.0 ± 0.8 sec (19.7 tones/min). On-response was validated by a 1-sec time window beginning 50 msec after tone initiation. The first tone was at 40 dB HL and went down (or up) in 10-dB steps as S pressed (or did not press) the switch. On a first reversal of direction the step changed to 5 dB. After 4 threshold-crossing series in 5-dB steps, the program stopped and the computer printed the mean of the 4 midpoints and the AD if the latter was less than 2.0 dB. If the AD was larger, 2 more series were run and the mean and AD printed excluding the 2 most divergent series.

REV	RANGE	THRES	SUM	MEAN	AD
20.00	—	—	—	—	—
10.00	10.00	15.00	15.00	15.00	0.0
18.00	8.00	14.00	29.00	14.50	0.25
10.00	8.00	14.00	43.00	14.33	0.28
18.00	8.00	14.00	57.00	<u>14.25</u>	<u>0.27</u>

HISTORY OF TEST

1-DB Steps

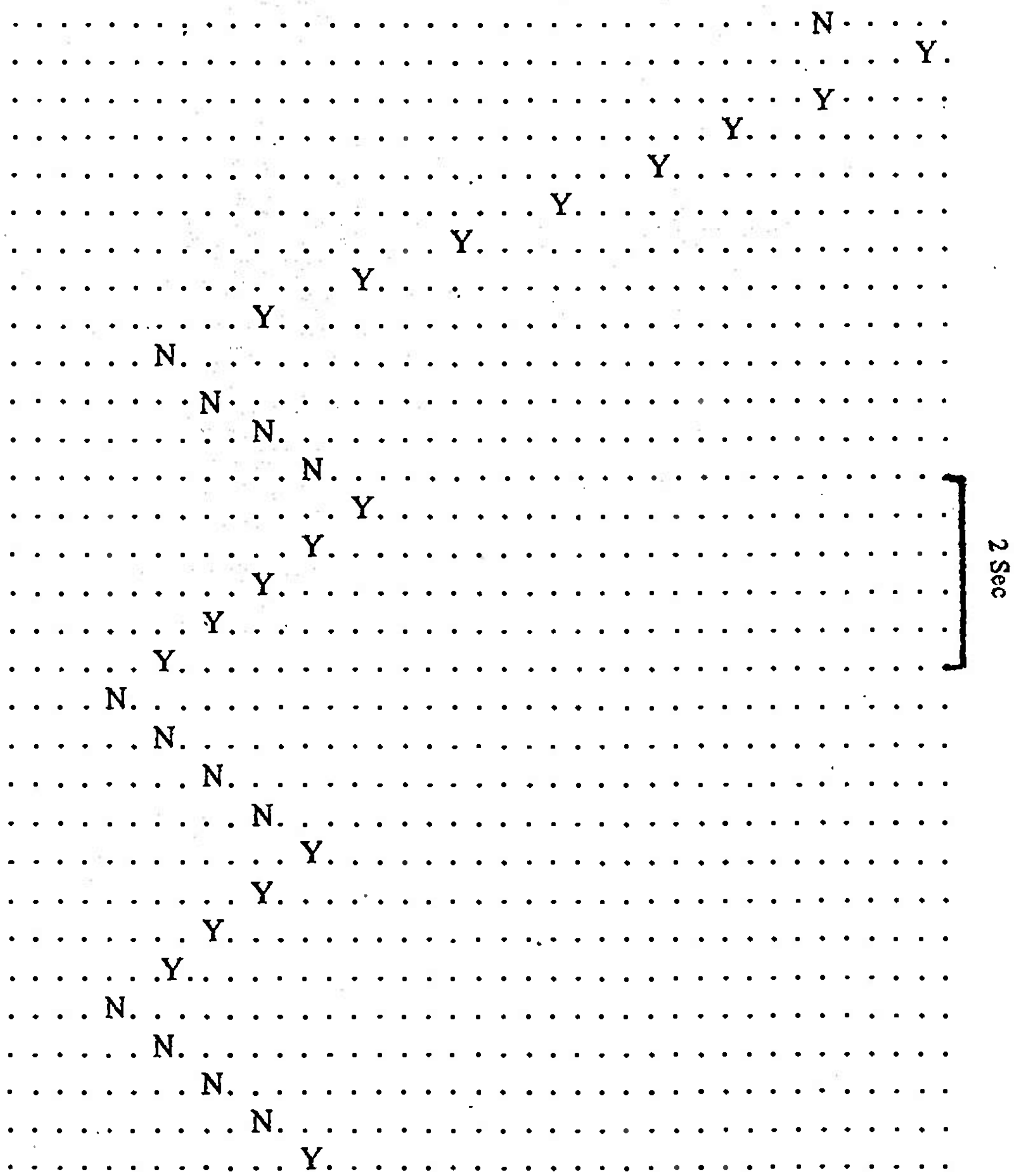

Fig. 1. Typical NSMRL Mark I Bekesy test. (If desired, only the underlined mean and average deviation need be printed and stored. For this S, 4 consistent threshold crossings were accomplished in 6 sec, including time to approach threshold region)

RESULTS AND DISCUSSION

A. Number of Acceptable Audiograms

Table I summarizes the data for 1767 HTLs (50 Ss x 3 procedures each test and retest x 6 frequencies = 1800, minus 33 HTLs not attempted when 7 Ss were called away before completing all 6 audiograms). The number of unacceptable initial runs was distributed about equally over procedures and frequencies and for test and retest. There was a total of 190 (about 10%) unacceptable initial

Table I. Number of HTLs Not Acceptable on First and on Second Runs
First figure: No. of HTLs not acceptable on first run
Second figure (in parenthesis): No. not acceptable after a second run

Freq	ANSI		Bekesy		ISO		
in KHz	Test	Retest	Test	Retest	Test	Retest	Total
.5	12 (2)	9 (1)	7 (3)	2 (0)	2 (0)	4 (2)	36 (8)
1	3 (0)	3 (1)	3 (2)	4 (2)	7 (1)	7 (1)	27 (7)
2	4 (1)	4 (4)	5 (3)	3 (2)	6 (1)	6 (2)	28 (12)
3	3 (3)	4 (3)	7 (2)	5 (5)	4 (4)	5 (1)	28 (18)
4	6 (1)	9 (3)	6 (2)	8 (3)	3 (3)	4 (2)	36 (14)
6	8 (2)	6 (3)	7 (1)	6 (1)	2 (0)	6 (2)	35 (9)
Totals:	36 (9)	35 (14)	35 (13)	28 (13)	24 (9)	32 (10)	190 (68)

HTLs which would ordinarily have demanded individual attention, but when the computer collected a quick second run, 122 or about 2/3 of these runs yielded acceptable HTLs. There remained 68 (3.8%) of HTLs needing individual attention. These were not distributed across Ss at random. The 68 HTLs which remained unacceptable even after a second run are portioned further by subject in Table II. No pattern could be observed for any procedure to be learned most readily, as might have appeared in an analysis of test-retest comparisons. In this population, quite typical of those for whom industrial HCPs are usually designed, no S had really major problems with any particular procedure. The worst cases were as follows:

(a) S:21 furnished 3 unusable HTLs on ANSI retest; 1 unusable HTL on Bekesy test and 3 on retest; and 2 unusable HTLs on ISO test and 1 unusable on retest (9 usable of 18).

(b) S:24 furnished 1 unusable HTL each on ANSI test and retest and on ANSI test; 3 unusable HTLs on Bekesy test; and 2 unusable HTLs on ISO retest (10 usable of 18).

(c) S:31 furnished 1 unusable HTL each on ANSI retest, Bekest retest, and on ISO test and retest; and 2 unusable HTLs each on ANSI test and Bekesy test (10 usable of 18).

(d) S:34 furnished 2 unusable HTLs each on ANSI test and on Bekesy test and retest (12 usable of 18).

(e) S:49 furnished 1 unusable HTL each on ANSI test and retest, 2 on

Table II. Distribution of Ss Needing Individual Attention (Neither Run Yielding Acceptable HTL)

ANSI				Bekesy				ISO			
Test		Retest		Test		Retest		Test		Retest	
S No.	Freq. in KHz	S No.	Freq. in KHz	S No.	Freq. in KHZ	S No.	Freq. in KHz	S No.	Freq. in KHz	S No.	Freq. in KHz
13	6	6	4	12	2	7	2	7	3	13	6
24	4	15	2	21	3	21	1,3,4	15	2	21	1
31	.5, 3	21	.5,2,3	24	1,2	22	4	21	1,3	22	4,6
34	.5, 3	24	6	31	2,4	31	3	22	4	24	2
35	2	26	3	32	.5	34	1,3	24	3	31	3
49	6	30	6	34	.5,1	37	2	31	3	35	2
50	3	31	4	37	6	42	3	49	4	41	.5
		36	2	48	.5,3	49	3,4,6	50	4	45	.5
		49	6	49	4					48	4
		50	1,4								
		52	3								

Bekesy test and 3 on retest (11 usable of 18).

(f) S:50 furnished 1 unusable HTL each on ANSI test, ISO test, and Bekesy retest, and 2 on ANSI retest (13 of 18).

Among the 50 Ss, 20 yielded acceptable HTLs in all 36 cases (3 procedures each test-retest x 6 frequencies), 12 Ss yielded 1 unacceptable HTL apiece, and 6 Ss yielded 2 unacceptable HTLs apiece. There were 8 Ss who yielded an average of 1–1.8 unacceptable HTLs and 4 Ss who yielded an average of 2 or more unacceptable HTLs per 6-frequency session. In most cases occasional unacceptable threshold-seeking runs could be taken care of by instructing the computer to retest those runs at the conclusion of the regular program, but it is probable in this population that Ss such as (a) – (f) above should be given individual attention by a qualified audiologist.

B. Test-Retest Reliability

Table III shows no real tendency for retest means or variances to change from those of the test. Retest means shift by more than 1 dB only 5 of 18 times, scattered over frequencies and procedures, and not always in the direction learning would cause. This table reveals that all three procedures perform quite well, and about equally well (r's = .88–.98) at 3, 4, and 6 kHz, but that at lower frequencies the Bekesy and ISO procedures (r's = .83–.91) outperform the ANSI (.72–.78). We do not know why this frequency difference should be the case.

(Some special interest attaches to test-retest reliability in Bekesy audiometry since Cluff (1980) reported such data for two standard procedures. His categories and data for a manual and for a Grason-Stadler 1703 audiometer are reproduced in Table IV, collapsed across 7 frequencies, together with comparable data from

Table III. Compares Test-Retest Statistics on Each Procedure

.5 KHz	N	Test	S.D.	Retest	S.D.	r	Change in Mean
ANSI	41	10.5	7.23	8.9	7.54	.78	–1.6
Bekesy	47	6.7	7.13	4.8	7.05	.84	–1.9
ISO	44	6.4	7.41	5.9	8.13	.90	–0.5
1 KHz							
ANSI	45	9.3	7.94	8.7	9.17	.77	–0.4
Bekesy	44	5.4	8.01	4.6	8.35	.83	–0.8
ISO	47	6.4	9.79	5.8	8.40	.87	–0.6
2 KHZ							
ANSI	45	8.9	9.64	8.6	11.33	.72	–0.3
Bekesy	41	2.3	9.36	1.9	9.88	.89	–0.4
ISO	45	5.0	10.00	5.3	9.01	.91	+0.3
3 KHz							
ANSI	42	11.1	16.02	11.7	16.95	.96	+0.6
Bekesy	45	6.0	16.30	5.6	15.63	.95	–0.4
ISO	44	8.8	16.66	7.5	17.09	.96	–1.3
4 KHz							
ANSI	44	14.3	17.87	14.1	18.47	.97	–0.2
Bekesy	44	9.2	18.18	9.3	18.58	.98	+0.1
ISO	44	12.2	18.75	10;8	18.47	.93	–1.4
6 KHz							
ANSI	44	12.0	16.71	13.8	19.92	.94	+1.8
Bekesy	45	8.5	18.00	7.8	16.93	.90	–0.7
ISO	46	7.2	17.29	7.1	17.27	.93	–0.1

Table IV. Test-Retest Agreement, Without Regard for Sign, Among HTLs for 31 Noise-Exposed Ss (from Cluff, 1980). Last Column Shows Comparable Data from the NSMRL Mark I Computerized Bekesy System

Differences in DB	Manual Test-Retest	Standard Bekesy Test-Retest (Rounded to 5 DB)	NSMRL Mark I Test-Retest (Rounded to 5 DB)
0	41.9	24.0	50.2
>0 (±5 ?)	42.4	41.9	40.5
>5 (± 10 ?)	12.0	24.9	6.8
>10 (± 15 ?)	0.9	6.0	1.1
>15 (± 20 ?)	0.9	1.4	0.7
>20	1.8	1.8	0.3
Total > 5	15.6	34.1	8.9

Entry: Percent of HTLs agreeing within specified limits.

the NSMRL Mark I system. Standard Bekesy audiometry yielded test-retest differences > 5 dB in 34.1% of cases, as compared with only 8.9% for the Mark I. The test-retest disagreement > 5 dB of 8.9% compares favorably with the figure of 15.6% for manual audiometry.)

C. Comparison of Group-Mean HTLs Among Procedures

When test and retest HTLs were averaged and compared, Table V shows that Bekesy and ISO HTLs were always fainter than ANSI HTLs by from 2.7–6.7 dB. Even after an allowance of a couple of decibels is made for the fact that the Bekesy and ISO programs interpret HTL as the 50%-correct point, while the ANSI HTL interprets the performance–intensity function at a higher confidence level, there remained a measurably fainter HTL for the "adaptive" methods. It seems most likely that this arose from the somewhat smaller intensity steps built into the latter methods. Recall that the ISO method never used 10 dB steps in its calculable series, and especially that the Bekesy program, which for 5 of the 6 frequencies yielded mean HTLs even lower than the ISO, was occasionally driven to the smallest 1-dB/step mode.

Table V. Means of Test-Retest HTLs (from Table III) Expressed in Relation to ANSI HTLs

Freq in KHz	Procedure	Mean of Test-Retest	Relative HTL	Freq in KHz	Procedure	Mean of Test-Retest	Relative HTL
.5	ANSI	9.7	0	3	ANSI	11.4	0
	Bekesy	5.7	–4.0		Bekesy	5.8	–5.6
	ISO	6.1	–3.6		ISO	8.1	–3.3
1	ANSI	9.0	0	4	ANSI	14.2	0
	Bekesy	5.0	–4.0		Bekesy	9.3	–4.9
	ISO	6.1	–2.9		ISO	11.5	–2.7
2	ANSI	8.8	0	6	ANSI	12.9	0
	Bekesy	2.1	–6.7		Bekesy	8.2	–4.7
	ISO	5.1	–3.7		ISO	7.2	–5.7

In any case, the regularity of these effects renders the differences trivial in an applied HCP, since a correction factor can easily be built into sets of data from any particular procedure to predict the results from any other.

D. Predictability Among Sets of Individual HTLs

Table VI interprets the group test-retest data in terms of the range within which 2/3 of the predictions of retest from test HTLs will fall. The table shows that the ANSI procedure is inferior in predictability at .5, 1, and 2 kHz ($S.E._{est}$ uniformly larger than for the Bekesy and ISO procedures), but that at other frequencies there is little to choose among procedures in this regard.

Table VI also shows that predictions of HTL at any frequency from one procedure to another are about as good as from test to retest within any procedure

Table VI. Standard Errors of Estimate Among the Three Procedures

	ANSI Test-Retest	Bekesy Test-Retest	ISO Test-Retest	ANSI vs Bekesy		ANSI vs ISO		Bekesy vs ISO	
KHz	$S.E._{est}$	$S.E._{est}$	$S.E._{est}$	r	$S.E._{est}$	r	$S.E._{est}$	r	$S.E._{est}$
.5	4.75	2.60	3.54	.85	3.59	.86	3.73	.87	3.61
1	5.96	4.66	4.12	.84	4.24	.84	4.71	.85	4.60
2	7.86	4.50	3.74	.84	5.10	.83	5.23	.90	3.81
3	7.16	6.88	7.18	.88	7.62	.98	3.31	.96	4.54
4	4.49	3.70	6.79	.94	6.21	.95	5.65	.96	5.07
6	6.77	7.38	6.39	.91	7.06	.93	5.79	.92	6.64

at that frequency. If one takes the ANSI data as standard, for example, Table VI shows that one can predict a Bekesy HTL from an ANSI HTL at least as well as one can predict a second ANSI HTL.

E. Time Required

1. Time to Complete One Six-Frequency Audiogram

Table VII gives the time taken on test and retest for the tone presentations using the 3 procedures. For the ANSI HTLs, the times taken (5.8 min on test, 5.5 on retest) were a bit longer than the times for the 12 normal-hearing Ss of D.A. Harris (1979b) taken manually in the ASHA procedure by experienced audiologists; in that study, 7-frequency audiograms were taken on both ears in a mean time of 4 min 3.5 sec per ear, clocked from the first to the last tone presentation following instructions and examples, as here. The range and variance were not reported. Possibly our industrial population was a bit more difficult to test, or possibly an experienced audiologist can justify shortening here and there either the tone duration or the intertone interval.

The Modified ISO procedure saves about a half minute over the ANSI procedure, presumably by not presenting an occasional pulse as faint as 10 dB below the final HTL as is sometimes required in the ANSI procedure. In addition it is noted that the variance of times for the initial test on the ISO procedure (S.D. = 0.66 min) is distinctly less than for the ANSI (S.D. = 2.41 min). The ISO in some way prevented a long-drawn-out search for 2 congruent series which in

Table VII. Time in Minutes to Present Tones (One Ear, Six Frequencies)

Procedure	Test Mn	Test S.D.	Test Range	Retest Mn	Retest S.D.	Retest Range
ANSI	5.8	2.41	3.5–15.8	5.5	1.42	3.5–10.3
Bekesy	1.8	.62	1.1–4.5	1.7	.48	1.0–3.1
ISO	4.5	.66	3.1–5.5	5.0	1.07	2.6–7.3

the extreme cases on the ANSI test consumed 7.6, 8.4, 9.4, 14.9 and 15.8 min before all 6 ANSI HTLs were either accepted or rejected. For the ISO test the greatest time consumed was 5.5 min.

The Bekesy far outperformed the others in time required. On the average, the time was 1.8 min, and the longest run was 4.5 min. This not only is very considerably shorter than the ANSI in either a manual or computer mode, but is also little more than half the time taken for today's commercial Bekesy fixed-frequency audiometer (30 sec/frequency for a 6-frequency audiogram = 3.0 min). Evidently in a high fraction of threshold-seeking runs an acceptable 4-crossing mean HTL was accomplished well before the 30-sec standard.

On the other hand, where it was needed, time was available to pursue an occasional run to 6 threshold crossings, or to starting another run altogether at the unsatisfactory frequency, and the vast majority of cases did in fact yield acceptable HTLs without individual attention, the most extreme case taking only 4.5 min.

There were scattered cases (8 at .5; 1 at 2; 5 at 4 kHz) where even after 6 threshold crossings were accomplished the AD of the 4 "best" midpoints still exceeded 2.0 dB. The computer had not been instructed to reject these thresholds, as it might have been, and start another entirely new run at the affected frequency, and these cases were included in those marked for individual attention. However, it is likely that had the computer been so instructed, most of the 14 unacceptable runs would have yielded acceptable HTLs.

2. Time Estimated to Test Both Ears of a Subject

A comparison was made of the time needed to complete two audiograms per S. Although these were test-retest on the same ear, this datum is our best estimate of the time it would have taken had the second ear been tested immediately after the first, as in usual audiometry. The times for each 6-frequency audiogram are in Appendix A. Table VIII gives the distributions of times (adding test and retest) for the three procedures.

a. ANSI Procedure. The median time (10.5 ± 1.07 min) was a bit longer than we would have predicted. There are to our knowledge very limited timing data in print on manual or computerized ANSI HTLs in an industrial HCP. We examined the responses to all pulses of the fastest S, who could hardly have yielded 12 HTLs in less time with this program, since for every HTL only two ascending series were required; nevertheless he consumed what would be 6.7 min for a two-ear audiogram. D.A. Harris (1979b) reported a mean of 7.06 min for a 14-HTL audiogram (i.e., 2 ears x 7 frequencies) by a qualified audiologist using the ASHA procedure (which demands at least three rather than only two ascending series per HTL) with a population of cooperative normal-hearing college students. This is an average of 20 sec per HTL. With the pace adopted for our ANSI procedure (3.8 sec/tonal pulse) there would be time in 20 sec to produce only about 5–6 pulses on the average per HTL; whereas Table IX (which gives the dis-

Table VIII. Test-Retest Combined Time in Minutes (i.e., Estimate for a Two-Ear Six-Frequency Audiogram

ANSI			Bekesy			ISO		
26.1	1		6.5	1		12.5	2	N: 49
24.5	1		6.9	0		12.0	1	Mdn: 9.25
17.1	1		5.5	1		11.5	2	Ave. Dev.: 0.63
15.7	1		5.0	1	N: 47	11.0	2	
			4.5	2		10.5	7	
13.5	2		4.0	7	Mdn: 3.35	10.0	3	
13.0	1		3.5	8	Ave. Dev.: 0.35	9.5	4	
12.5	3		3.0	10		9.0	6	
12.0	2		2.5	12		8.5	5	
11.5	3		2.0	5		8.0	9	
11.0	4					7.5	3	
10.5	4					7.0	4	
10.0	6	N: 47				6.5		
9.5	3					6.0		
9.0	7	Mdn: 10.50				5.5	1	
8.5	2	Ave. Dev.: 1.07						
8.0	4							
7.5	1	Range: 6.7–26.1						
7.0	0							
6.5	1							

tribution of the number of pulses presented in all 550 of the ANSI runs for which such data were complete) shows that the median number of pulses presented was 13.2, or about 50 sec per HTL.

Robertson et al (1979) for sensorineural Ss reported 6.9 min for a manual ASHA procedure, or 35 sec per HTL. This would allow about 10 tone pulses at our pace. Clearly the time consumed in manually collecting ASHA HTLs with the sensorineural Ss of Robertson et al is still a bit faster than the pace adopted

Table IX. Distribution of Number of Pulses to Complete Individual HTLs by the ANSI Procedure

	N	%	
49-51	1	.18	
46-48	0		
43-45	0		
40-42	3	.5	N: 550
37-39	5	1.0	
34-36	1	.18	Mdn: 13.18
31-33	7	1.3	
28-30	12	2.2	
25-27	11	2.0	
22-24	10	1.8	
19-21	37	6.7	
16-18	75	13.6	
13-15	120	21.8	
10-12	199	36.2	
7-9	69	12.6	

here for ANSI HTLs. In order to tailor our pace to that of the audiologists in the survey of Robertson et al, shortening the two-ear audiogram by 3.5 min, it would be necessary to reduce each of the 158 events (13.2 pulses/HTL x 12 HTLs) by 1.52 sec. This could easily be done by reducing the tone duration to 0.5 sec (thereby ignoring the ASHA–ANSI recommendation of 1 sec or more) and the intertone interval to 1.8 ± 0.8 sec. The effect especially of the latter change on HTLs in an industrial HCP remains to be determined but our impression is that it would have for some Ss a markedly deleterious effect.

The extra time taken in collecting these HTLs over that taken by manual audiometry by an industrial certified audiometric technician is counterbalanced by an overall look at testing. Table IX shows that substantial numbers of threshold-seeking runs were pursued by the computer until a satisfactory HTL was established even though far more tones were presented than the 18 often considered a limit for a particular run. There were in fact 87 (16%) of all HTLs which required more than 18 pulses, even up to 51, to establish HTL. Note, however, that the program alone handled nearly all of these HTLs without the necessity for the audiometrist to call in a certified audiologist. Thus the overall time required of testing personnel at all levels was saved even though some HTLs unduly lengthened the average testing time.

b. Bekesy Procedure. Table VIII gives the estimated two-ear median testing time of 3.35 min for a 6-octave audiogram. Fifty per cent of all Ss required within 3.0–3.7 min. This is quite comparable to the Ss of a previous population given NSMRL Mark I Bekesy audiometry (Harris and Smith, 1979), who used 12.7 sec/HTL (= 2.54 min for 12 HTLs).

The time of 3.35 min/S can be directly compared to the fixed time of 6 min for the program of the usual industrial self-recording Bekesy audiometer. It excells by a factor of 2 to 3 other systems either manual or computerized. Robertson et al (1979), for example, report a testing time with a computerized ASHA-procedure unit of 6.2 min on normals and 8.0 min on sensorineural-loss Ss. D.A. Harris (1979a) with an industrial population found a testing time of 11.77 min with a computerized ASHA procedure, but stated that the unit was later "modified to reduce testing time to slightly over 7 min without apparently altering the accuracy of measurement." Thus on normal-hearing college students (1979b) he found a mean test time of 7.25 min.

NSMRL Mark I audiometry has therefore yielded testing times no longer than half as long as any other system found in or proposed for industrial HCPs.

c. Modified ISO Procedure. Table VIII gives the group data. The median test time, 9.25 min, is slightly shorter than that for the ANSI procedure, but the overlap is almost complete. A real difference may arise in that the Ss who consumed the longest time determining ANSI HTLs (from 15.7–26.1 min) did not consume more than 12.5 min with the ISO procedure.

d. Savings in Computerized Bekesy Audiometry. Although it may be possible to fine-tune the ANSI program to yield acceptable HTLs yet speed to about

two-thirds the present pace, the ANSI-Bekesy differences in the data of this paper must be considered. Table X gives the distribution of differences for the estimated two-ear audiogram by the ANSI time minus the Bekesy time. The least savings was 4.3 min, and extended up to 20.2 min for the S who had the least efficient ANSI audiograms. The median time saved was 7.27 ± .95 min. Thus, for 50% of the Ss of such a population the savings would lie between 6.32–8.32 min per S by using a computerized Bekesy paradigm.

Table X. Savings in Minutes Per Subject by Using NSMRL Mark I Computerized Bekesy Over Standard ANSI Audiometry (Estimated Time to Complete Two-Ear Audiogram Using Six Frequencies)

20.2	1
19.3	1
14.5	1
10.5	1
10.0	4
9.5	0
9.0	2
8.5	3
8.0	1
7.5	4
7.0	11
6.5	6
6.0	3
5.5	1
5.0	3
4.5	4
4.0	1

N: 47

Mdn: 7.27

Range: 4.3–20.2 min

Effective HTL Interval Size (the Rounding Problem) in Bekesy Audiometry

The imprecision has been argued extensively (Harris, 1978) of an audiometric program in which one can have confidence only within a range of 10 db (i.e., ± 5 dB). In such a case, an HTL in a monitoring audiogram must shift from the reference audiogram at that frequency by > 10 dB before it can be considered beyond chance expectation. The confidence in a threshold audiogram can of course be increased if the HTLs in a reference audiogram are means, to the nearest 5 dB, of 2 and preferably 3 independent audiograms, and each monitoring audiogram the same. It is, however, not often that time can be devoted to multiple audiograms within the same testing session.

There are numerous reasons why retest may differ from test HTLs, even within a single session and even with the earphone not moved between threshold-seeking runs. Some of these sources of variance may be rendered of less degree if

the most efficient psychophysical procedures are used and if everything is standardized that can be standardized in threshold-seeking runs. It was the intent of NSMRL Mark I Bekesy audiometry to create such conditions.

One such condition involves step size. Harris (1954) showed that when 1-dB steps were used in the traditional method of limits, and each series was scored to the nearest 0.5 dB, 5 Ss yielded standard deviations of from .67 – 1.06 dB at 1 kHz and from .60 – 1.10 dB at 8 kHz (40 4-crossings audiograms over 5 days). But this "grain" of about ± 1 dB in such audiometry rises when a 5-dB step size is used: standard audiometry on 64 Ss yielded test-retest average deviations of 2.1, 2.5, 2.1, 4.1 and 3.4 dB at octaves .5–8 kHz in order (Harris, 1945).

In the present material, the Bekesy interval for calculable series was a 2-dB step (i.e., 5 dB/sec) unless that was too rapid for a S, in which case it dropped to 1 dB/step (i.e., 2.5 dB/sec). These are step sizes shown to be efficient for audiometry by the method of limits, and which render it possible to provide a HTL as a mean to the nearest decibel of 4 midseries points. Of course, the variance in audiometry at its best is such that HTL to the nearest decibel is hardly to the significant figure. It is possible that the significant figure is not the decibel value, or the nearest 5-dB category, but something between. The present Bekesy data render feasible a conclusion that the significant figure can be considered to be the nearest 2.5-dB category.

Table XI shows comparative distributions of HTL test-retest differences when the individual HTLs were first rounded to the nearest 2.5-, and the nearest 5-dB categories. The last row shows that the coarser interval categorized from 36 – 67% (mn = 50.0 across frequencies) of HTLs as varying by 5 dB or more, while the finer interval categorized from 13 – 39% (mn = 24.3 across frequencies) as varying by 5 dB or more. In the positive mode these figures mean that by rounding to 2.5 dB it could be said that for ¾ of these HTLs, rather than for ½, the test-retest grain is significantly less than 5 dB.

Table XI. Distribution of Test-Retest Differences in Percent When HTLs were First Rounded to the Nearest 2.5- and 5.0-DB Intervals

	Frequency in KHz											
	.5		1		2		3		4		6	
Test-Ret.	Rounding Intervals											
Diffs.	2.5	5.0	2.5	5.0	2.5	5.0	2.5	5.0	2.5	5.0	2.5	5.0
0	30	45	16	48	43	63	30	48	34	64	31	33
± 2.5	45	–	61	–	40	–	42	–	52	–	29	–
± 5.0	13	45	11	43	10	29	21	48	2	27	24	51
± 7.5	6	–	5	–	0	–	5	–	7	–	2	–
±10.0	4	9	2	5	5	7	0	2	2	9	4	9
>10.0	2	2	5	5	3	0	2	2	2	0	9	7
⩾ 5.0	25	56	23	53	18	36	28	52	13	36	39	67

It is certainly unjustified, given the sources of variance, to enter HTL to the nearest dB, though indeed an international draft of audiometric procedures (Anon., ISO, 1977) recommends just that. It may even be naive, given the current audiometric picture, to round to the nearest 2.5 dB. But it is demonstrable here that such rounding would result in reducing one source of variance, and in any case the procedure is very easy and certainly can do no harm.

The fact that other sources of variance are present, though eradicable, is no excuse not to tend to this one when, as now, it becomes possible and convenient. Other sources of variance are indeed being aggressively pursued: hundreds of audiometric booths and trailers are entering HCPs, audiometric technicians are being trained in droves with excellent courses and materials, audiometers are now available with frequency and intensity calibration exceeding by far the still rather lax ANSI specifications, circumaural cushions are being designed to supplant the poor test-retest fit on many ears of the MX cushion, and so on. Already the recommendations of OSHA (Stender, 1974) have had a most salubrious effect, and the situation is today far better than only a few years ago. Each piece of the puzzle will eventually fit into an ever brighter picture.

SUMMARY

Three audiometric procedures were programmed at .5, 1, 2, 3, 4, and 6 kc/s and presented on test and retest to 50 persons: (1) a version of the Amer. Nat'l. Standards Inst. guide-lines (the 10-db down—up 5 db" rule) incorporating time-window response validation, (2) a slight modification of the procedure recommended by the Internat'l. Standards Organization, and (3) the NSMRL Mark I Bekesy-type system. (a) incorporating numerous quality controls, (b) providing not only an estimate of Hearing Threshold Level (HTL) to the nearest db but providing also an estimate of the confidence to be placed in each HTL, and (c) continuously adapting its parameters to interact with the behavior of the testee. Initial threshold-seeking runs, if they yielded no HTL or if response pattern did not meet quality standards (about 10% of all initial runs) were immediately followed by a second exactly similar run. This step yielded acceptable HTLs in 96.2% of all cases, about the same for all procedures. Six Ss accounted for 2/3 of failures. Test-retest reliability was high (r = .83–.98) except that the ANSI procedure was less so at .5, 1, and 2 kc/s (r =.72–.78). Test and retest group-mean HTLs never changed by as much as 2 db. Individual test-retest differences of 5 db or less were found in 90.7% of cases for the Mark I, compared with 65.5% reported by Cluff (1980) using a standard Grason-Stadler 1703 Bekesy audiometer. ISO HTLs were fainter by 3.6, 2.9, 3.7, 3.3, 2.7, and 5.7 db than ANSI HTLs, while the Mark I HTLs were fainter than ANSI HTLs by 4.0, 4.0, 6.7, 5.6, 4.9, and 4.7 db in the usual frequency order. Prediction of an individual S's HTL by any procedure could be accomplished as efficiently from any other procedure as could prediction from test to retest within any procedure. Estimated time to complete a two-ear audiogram on the average S was 10.5 ± min for

the ANSI, 9.25 ± 0.63 min for the ISO, and 3.35 ± 0.35 min for the Mark I; average savings for individual Ss with the Mark I vs the ANSI procedure was 7.27 min (range 4.3–20.2 min). It was shown that HTLs furnished by a computerized adaptive Bekesy system can profitably be reported to the nearest 2.5 db. The Mark I system was shown, by all criteria examined here, to be the equal of, or more usually superior to, the other classes of procedure as the audiometric method of choice in hearing conservation programs.

ACKNOWLEDGEMENT

A work such as this can only be a cooperative effort among many persons. I thank Dr. Tom Santoro for creating the ANSI and Bekesy computer programs used here and in precursor papers, and especially for the Modified ISO program used here for the first time. I thank Paul F. Smith for monitoring the equipment generally and for precise calibration, and for many pleasant discussions on the possibilities inherent in these and other similar audiometric programs. I thank Chris Eident of the Industrial Health Department of the USN Regional Medical Center, Groton, Connecticut, for furnishing subjects from his HCP, and I thank those subjects for donating extra time to the furtherance of this study. I have acknowledged the contribution of Deborah Kopko and Kathy Levanti in the body of this paper. Finally I wish to express my gratitude to Robert A. Margulies, CDR, MC, USN, Commanding Officer of NSMRL, for permitting me to use the facilities of the Laboratory to bring this work to final publication.

This is NSMRL Report No. 930. The opinions expressed here are those solely of the author and do not necessarily reflect the official views of the U.S. Navy.

REFERENCES

Anon, Amer. Nat'L Standards Inst. "Methods for Manual Pure-Tone Threshold Audiometry." ANSI–S.3.21.

Anon, International Standards Organization. "Pure Tone Thresold Audiometry on Occupational Noise-Exposed People. First Draft Proposal ISO/DQ 6189 prepared by ISO/TC 43: Acoustics; Writing Group 3 "Techniques for Audiometry." March 1977.

Anon, Amer. Speech Hear. Assoc. "Guidelines for Manual Pure-Tone Audiometry." ASHA, 1978, 20, 297-301.

Brogan, F.A. A discrete-frequency automatic audiometer simulating manual technic. USAF Sch. Av. Med. Report SAM–TR–56-123, Randolph AFB, Texas, Sept. 1956.

Cluff, G.L. Audiometry reliability with a noise exposed population. Sound & Vibration, Jan 1980, 14, 18-20.

Harris, D.A. Microprocessor versus self-recording audiometry in industry. J. Aud. Res., 1979a, 19, 137-150.

Harris, D.A. Microprocessor, self-recording and manual audiometry. J. Aud. Res., 1979b, 19, 159-166.

Harris, J.D. Group audiometry. J. Acoust. Soc. Am., 1945, 17, 73-76.

Harris, J.D. Experiments in fluctuation of auditory acuity. J. Gener. Psychol., 1954, 50, 87-109.

Harris, J.D. A comparison of two national standards for estimating audiometric threshold for pure tones. Progr. Ann. Meeting Amer. Auditory Soc., San Francisco, California, Nov. 1978. Report No. 890, U.S.Naval Submarine Base Medical Research Laboratory.

Harris, J.D. Optimum threshold crossings and time-window validation in threshold pure-tone computerized audiometry. J. Amer. Acoust. Soc., 1979, 66, 1545-1547.

Harris, J.D. and Smith, P.F. A comparison of a standard and a computerized adaptive paradigm in Bekesy fixed-frequency audiometry. J. Aud. Res., 1979, 19, 1-22.

Hughson, W. and Westlake, H. Manual for program outline for rehabilitation of aural casualties both military and civilian. Trans. Amer. Acad. Ophthal. Otolaryngol., Suppl. 48, 1944, 1-15.

Loyborg, T.W., Fankhauser, C.E. and Strom, C.G. A clinical trial of three microprocessor audiometers. Progr. Nat'l. Noise & Vibr. Control Conf., Chicago, Ill. (NOISEXPO 80) 1 May 1980.

McMurray, R.F. and Rudmose, W. An automatic audiometer for industrial medicine. Noise Control, 1956, 2, 33-36.

Robertson, R.M., Greene, J.W., Maxwell, D.W. and Williams, C.E. Exploratory assessment of automated hearing test systems. Report 1263, Nav. Aerosp. Med. Res. Lab., Pensacola, Florida, Oct 1979.

Schientz, R.J. Industrial auditory monitoring in compliance with OSHA. Hear. Instr., 1980, 31, pp. 7,8,12.

Weiss, E. A computing automatic audiometer for testing hearing loss. Digest, 1961 Int'l. Conf. Med. Electronics Engnrs. P.L. Frommer (Ed.) 1961.

APPENDIX A

Hearing Threshold Levels for Each Subject for Each Procedure at the Frequencies .5, 1, 2, 3, 4, and 6 Kc/s in Order, and Time in Minutes for the One-Ear Audiogram

A: ANSI Procedure. B: NSMRL Mark I Bekesy Computerized Audiometer. C: Modified ISO Procedure. t: Test; r: Retest

S:1	A:t	30	35	35	40	45	50	3.5	S:2	A:t	15	20	10	25	25	15	4.5
	r	30	35	35	35	45	53	3.2		r	10	15	20	25	25	25	4.2
	B:t	26	31	31	34	41	44	1.1		B:t	11	15	−1	16	16	13	2.1
	r	29	32	32	32	40	43	1.3		r	10	14	4	10	23	16	1.7
	I:t	29	34	35	35	43	54	3.0		I:t	11	18	5	21	22	14	4.1
	r	30	34	31	34	42	50	2.6		r	6	11	3	18	22	15	a
S:3	A:t	b	20	5	10	0	10	5.1	S:4	A:t	b	20	10	0	10	5e	14.9
	r	0	15	5	c	c	c	d		r	0	15	5	0	10e	10	9.6
	B:t	1	12	4	3	−1	7	1.3		B:t	1	12	4	−6	2	2	2.4
	r	4	15	8	8	2	−3	1.1		r	4	15	4	−3	3	3	1.9
	I:t	1	13	5	5	−5	10	3.9		I:t	1	13	5	−2	5	5	4.1
	r	0	13	7	10	9	−6	4.2		r	0	13	3	2	2	2	3.9
S:5	A:t	6	15	10	5	5	5e	4.2	S:6	A:t	20e	25	15e	10	10e	20	9.4
	r	0	25	5	10	10	10	5.8		r	15	10	0	5	f	40	7.7
	B:t	1	10	4	4	5	2	1.5		B:t	2	2	−2	−4	−2	1	1.6
	r	4	7	4	6	4	3	1.4		r	3	5	0	1	2	5	1.0
	I:t	1	6	5	3	30	5	4.2		I:t	5	5	2e	2	−14	7	5.5
	r	0	5	3	7	0	2	4.2		r	4	5	−1e	−2	−8	6	5.9
S:7	A:t	5	10	10	5	5	−5e	5.3	S:8	A:t	10	15	0	5	10	5	4.2
	r	0e	10	10	5	5	0	6.6		r	5	10	0	5	10	0	4.2
	B:t	−8e	2e	1	−1	1	−9	2.7		B:t=	7	9	−2	3	9	−12	1.3
	r	2	0	f	−7	−12	5	1.6		r	9	4	2	−4	11	1	1.2
	I:t	5	38e	10e	4	13	9	4.8		I:t	6	5e	1	8e	10	−2	5.5
	r	10e	10e	11	f	14	−7	6.1		r	3	9e	0e	4	7	−11	5.4

(S:10 not completed)

S:9	A:t	15	20	5	0	15	5	4.6	S:14	A:t	20	5	5	05	10	5	6.0
	r	25	35	25	10	15	15	3.5		r	20e	10	5	−5	5	0	5.2
	B:t	15	26	17	−2	7	−8	1.7		B:t	15	2	−1	−12	0	−7	1.6
	r	16	25	18	−4	14	−2	1.5		r	13	2	−1	−9	2	−8	1.9
	I:t	21e	30	26	9	9	13	4.6		I:t	19	7	4	−7	5	−4	4.8
	r	17	29	24	4	9	−1	4.0		r	17	6	3	−8	1	−6	5.7
S:11	A:t	0	0	15	0	5	35	4.3	S:15	A:t	0	f	−5	−5	10	0	4.4
	r	0	6	15	5	5	35	4.0		r	0	−5	f	0e	15	−5	5.3
	B:t	−6	−7	3	−5	3	33	1.7		B:t	14	9	−5	−9	−2	−11	1.3
	r	−6	−6	4	−6	4	32	1.6		r	−3	−5	−7	−9	1	−8	1.3
	I:t	−5	−3	9	−1	3	30	4.1		I:t	−3	−8	f	−4	1	−8	4.6
	r	−4	−1	7	0	6	34	a		r	−1	−1	−9	−7	−8	−6	6.0
S:12	A:t	b	5	5	5	5	5e	7.6	S:16	A:t	5	5	0	0	5e	5	5.4
	r	−5	0e	−5	−5e	5	10	6.3		r	5	5	0	0	5	0	4.6
	B:t	−6	−4	f	−4e	0e	4	3.1		B:t	1	1	−8	−6	−1	−1	1.4
	r	−6	−5	−11	−8	−1	5e	2.7		r	−1	0	−9	−5	2	2	1.6
	I:t	−2	−1e	−5	2	7	11	4.8		I:t	4	2	−6	−2	2	2	4.8
	r	−3	−4	−5	−1	2	9	4.6		r	−2	1	−4	−3	0	0	5.3
S:13	A:t	f	15	10	−5	5	f	a	S:17	A:t	10	5	15	50	50	20	4.8
	r	15	10	5	0	0	−5	5.4		r	15	0	30	60	55	20	4.4
	A:t	17	11	0	−7	−1	−15	1.6		B:t	13	6	17	42	42	24	1.4
	r	13	7	2	−8	1	−10	a		r	3	−1	14	46	44	19	1.2
	I:t	14	11	1	−5	−1	−5	3.7		I:t	7	−2	14	49	46	25	3.8
	r	15	13	6	−12e	2	f	a		r	3	1	14	47	45	26	3.5

S:18	A:t	15	15	0	5	0	0	4.2
	r	10	10	5	5	5	5e	5.1
	B:t	10	12	–6	1	–3	–12	1.2
	r	7	12	–3	3	1	–13	1.2
	I:t	a	a	a	a	a	a	a
	r	5	13	–5	2	–1	–14	4.2
(S:19 not completed)								
S:20	A:t	15	10	0	10	5	15	4.4
	r	5	10	0	5	5e	10	5.4
	B:t	4	0	–7	0	–5	8	1.4
	r	2	4	–8	2	–6	3	1.3
	I:t	3	5	–6	5	–1	9	4.0
	r	1	6	–3	1	1	11	4.2
S:21	A:t	5	5	–5	–10	15	15e	7.0
	r	f	–5	f	f	15e	25	6.3
	B:t	0	–7	–6	f	–3	5	1.6
	r	0	f	–6	f	f	13	1.5
	I:t	1e	f	–1	f	6	–6	4.9
	r	1e	f	–4e	–14	–4	9e	6.7
S:22	A:t	a	a	a	a	a	a	a
	r	a	a	a	a	a	a	a
	B:t	14	3	3	–10	–12	- 4e	2.2
	r	11	0	1	–6	f	–2e	2.2
	I:t	15	4	4	–2	b	–1	4.3
	r	11	2	2	–7e	f	f	5.9

S:23	A:t	5	5	15	20	15	0	4.8
	r	5	5	20	20	15	5	4.5
	B:t	0	0	9	13	10	5	1.3
	r	1	2	9	14	9	5	1.1
	I:t	1	1	13e	13	10	–7	4.6
	r	–2	2	8	13	9	9	a
S:24	A:t	15e	15	15	5	f	15e	15.8
	r	20	15	15	20	5	f	10.3
	B:t	10	f	f	0e	6e	10	14.5
	r	8	12	16	5	8e	24	2.3
	I:t	12	10e	5	f	27	–9	5.2
	r	23e	10	f	1	2	10	7.3
S:25	A:t	–5	0	10	5	5	0e	5.9
	r	–5e	0	5	5e	–5	5	6.5
	B:t	–4	2	11	1	5	3	1.6
	r	–12	–2	1	4	3	–1	a
	I:t	–6	–3	7	5	1	–5	4.4
	r	–10	–2	3	6	1	5	4.2
S:26	A:t	5e	5	0	–5	5	5	5.9
	r	b	0	–5	f	10	5	4.7
	B:t	2	4	–9	–12	4	–1	1.8
	r	0	–3	–4	–13	3	4e	2.3
	I:t	0	3e	–6	–14	3	6	5.3
	r	–1	–2	0	–14	6	2	4.6

S:27	A:t	20e	15	10e	5	15	10	6.8
	r	20	20	10	5	15	10	5.8
	B:t	19	17	11	6	13	1	1.2
	r	17	14	7	7	16	–4	1.3
	I:t	20	19	11	8	16	1	3.7
	r	22	17	10	2	15	3	3.9
S:28	A:t	10	10	0	10	10e	20	5.8
	r	10	5	0e	10	5	20	5.3
	B:t	7	2	–11	5	–1	17	2.0
	r	4	1	–12	3	–1	16	2.0
	I:t	7	9	–3	10	11	10	4.0
	r	7	9	–3	11	10	12	4.1
S:29	A:t	0	10	0	0	0	10	5.9
	r	5	5	0	5	5e	15e	7.7
	B:t	6	8	1	1	4	7	1.8
	r	1	5	–1	–2	4e	8	2.7
	I:t	2	3	–3e	–1	–6	10	5.2
	r	–1	5e	–3	–2e	–6	12e	6.7
S:30	A:t	10	10	15	5	10	7e	5.2
	r	10	10	15	0	10	f	5.1
	B:t	15	15	12	5	12	–7	2.1
	r	12	12	13	2	4	–7	1.7
	I:t	9	9	13	–2	10	7	4.5
	r	7	7	13	–3	6	9e	5.0
S:31	A:t	f	f	10	f	25	5	8.4
	r	0	00	10	40	f	25e	7.3
	B:t	–2	–2	f	–12	f	5e	2.3
	r	–2e	–2e	7e	f	–8	2	3.1
	I:t	3	3	11	f	10	–8	4.9
	r	3	3	10e	f	5	–8e	7.2
S:32	A:t	10	10	–5	5	–5	10	3.9
	r	5	5	–5	5	0	10	4.5
	B:t	f	f	b	2	–4	8	a
	r	2	2	–12	2	–77	7	1.6
	I:t	1	1	–9	2	–5	6	5.0
	r	–1	–1	–6	–1	–4	7	4.2
S:33	A:t	20	15e	15	10	15	5	54.
	r	10	10	15	5	15	5e	6.5
	B:t	8	7	9	5	14	10	1.5
	r	11	10	8	10	15	10	1.7
	I:t	10	11	10	6	13	4	3.7
	r	6	14e	6	9	16	2	4.7
S:34	A:t	f	b	b	f	b	25	a
	r	20e	25	40	35	35	25	3.9
	B:t	f	f	b	b	b	b	a
	r	16	f	b	f	33	b	a
	I:t	17	14	29	26	28	17	3.9
	r	19	13	26	26	30	18	3.5

S:35	A:t	5	5	f	0	5	0	4.8
	r	5	5	−5	5	0	−5	5.4
	B:t	3	1	−11	−1	−4	−9	1.4
	r	−1	−2	−9	−5	−4	−8	1.5
	I:t	2e	1	−6	1	5	−6	5.5
	r	2	3e	f	−1	4	−3	5.3
S:36	A:t	5e	0	−5	15	20	0	6.1
	r	10	5	f	20	15	0	6.0
	B:t	10	2	−11	13	16	−2	1.6
	r	5	0	−13e	13	19	−7	1.9
	I:t	4	−1	−11	13	14	−12	4.9
	r	10	5	10	20	15	−5	a
S:37	A:t	5	10	35	15	10	5	5.0
	r	5	5	35	15	10	5	4.2
	B:t	2	7	14	10	13	f	2.0
	r	3	6	f	9	10	−7	2.2
	I:t	0	5	21	13	8	−6	4.4
	r	1	6	20	11	10	−11	4.5
S:38	A:t	5	0	5	5	10	−5	4.6
	r	5	0	5	5	15	−10	5.1
	B:t	12	11	10	12	11	0	1.4
	r	9	6	5	7	7	−4	1.2
	I:t	6	3	5	7	6	−9	4.5
	r	2	2	4	6	5	−10	4.3

S:39	A:t	5	5	5	15	15	5	5.1
	r	5	5	0	15	20	5	4.3
	B:t	1	−2	2	12	7	15	1.5
	r	0	−1	6	14	8	12	1.4
	I:t	3	3	1	14	15	−2	4.5
	r	2	2	5	15	19	−1	4.8
S:40	A:t	10	15	15	5	15	0	4.9
	r	5	30	35	5	10	0	5.3
	B:t	10	17	8	2	10	4	1.7
	r	7	19	19	1	13	3	2.2
	I:t	5	14	10	5	9	2	3.9
	r	5	7	8e	1	9	0e	5.8
S:41	A:t	10	5	35	10	10	10	6.4
	r	10	10	5	5	5	10	4.8
	B:t	9	−2	−4	−4	−4	13	2.0
	r	2	−4	−6	−4	−4	12	2.1
	I:t	−1	−5	1	0	−3	5	4.9
	r	f	−8	−2	0	−3	9	5.4
S:42	A:t	10	5	0	0	0	−5	5.1
	r	0	0	0	0	5	−10	5.8
	B:t	−1	0	−2	−10	−10	−3	1.8
	r	−4	−7	−8	f	−8	−12	2.0
	I:t	−1	−4	−2	−9	−1e	−13e	6.3
	r	−2	−5e	1	−12	−5e	−13	6.4

S:43	A:t	10	0	0	0	5	0	4.4
	r	10	5	0	0	5e	–10	4.6
	B:t	7	–1	–1	–2	6	–4	1.6
	r	4	–2	–1	–3	3	b	1.3
	I:t	6	0	–1	–1	5	–5	4.3
	r	5	–3	–2	–3	2	–10	4.2
S:44	A:t	10	10	15e	5	5	25	6.1
	r	0	20e	15	10	10	30	6.7
	B:t	8	10	12	7	0	20	1.1
	r	4	8	12	5	–3	17	1.1
	I:t	2	6	11	19	f	18	5.2
	r	3e	10	13	8	2	20	5.6
S:45	A:t	25	15	15	50	55	60	4.2
	r	15e	15	20	50	60	65	4.9
	B:t	12	9	11	42e	53	45	1.7
	r	13	9	9	41	52	46	1.4
	I:t	10	11	14	47	55	51	4.2
	r	f	13	15	49	55	50	5.0
S:46	A:t	15	25	10	55	85e	70	5.3
	r	15	20	0	60	80	70	5.4
	B:t	13	19	–2	50	74	65	2.0
	r	9	17	–1	51	77	66	1.6
	I:t	13	22	–1	55	80	59	4.2
	r	11	22	–1	53	79	58	3.6

S:47	A:t	15	10	10	55	55	55	3.5
	r	15	5	15	55	55	55	4.4
	B:t	8	3	7	49	52	47e	1.9
	r	9	4	9	51	55	46	1.5
	I:t	9	7	11	54	55	49	3.7
	r	13	7	13	53	55	48	4.1
S:48	A:t	10	10	10	20	30	20	4.3
	r	10	5	10	20	35	20	4.2
	B:t	f	72	f	40	35	49e	1.6
	r	6	0e	–4	15	25	16	2.1
	I:t	11	4	2	17	26	2	3.4
	r	7e	3	3	18	f	8	5.0
S:49	A:t	15	0	0	–5	0e	f	6.1
	r	10	0	–5	–5	–5e	f	5.4
	B:t	8	–5	–9	9e	f	oe	3.0
	r	1	–3	–10	f	b	f	1.5
	I:t	3	–3	–5	–7	–8	–4	5.1
	r	–4e	–6	–6	–11	–5e	–6	5.9
S:50	A:t	0	0	0	f	5	5	6.0
	r	–5	f	5	–5e	f	0	6.9
	B:t	1	1	–5	–14	–13	–6	1.4
	r	1	–3	–5	–9	–14	–5	1.4
	I:t	–1	–1	–1	–8	f	1	4.1
	r	1	–1	2	–8	–9	–2	5.3

S:51	A:t	15	5	5	0	−5	0	5.9
	r	5	0	0	f	−10e	0	5.5
	B:t	5	3	0	−8	2	6	1.4
	r	5	c	c	c	c	c	c
	I:t	5	4	2e	−11	−7	−2	5.4
	r	c	c	c	c	c	c	c
S:52	A:t	5	0	−10	5	10	10	a
	r	10	5	−10	−5	5	0	a
	B:t	0	−2	−9	−4	1	−10	a
	r	2	−3	−9	−3	1	−5	a
	I:t	3	−2	−10	−6	1	−8	a
	r	3	−2	−14	−3	−1	−3	a

a: Inadvertently not retained by computer (operator error)
b: Criterion not reached in first run. Second run inadvertently not attempted
c: S not available
d: Audiogram incomplete
e: Second run required
f: Second run also did not reach criterion
g: Audiogram inadvertently not collected